LCA Methodology

Allocation of Process Gases Generated from Integrated Steelworks by an Improved System Expansion Method

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Abstract

Goal, Scope and Background. Although a large number of life cycle inventory (LCI) analyses for steel-making processes or steel products have been conducted, the allocation of process gases generated from the steelworks has not yet been clearly solved. The most consistent settlement for avoiding the allocation problem has been generally known as a system expansion method. However, the existing subtracted operations for the process gases in that method are inconsistent to a system in which those gases are consumed at their unbalanced consumption ratio. The goal of this study is to suggest a more reasonable substitute for the process gases in the system expansion method and a modified system expansion method resettling the amount of process gases used.

Methods. To seek a more suitable one as a substituted operation of the process gas, a kind of by-product gas, in the system expansion method, it is necessary to analyze the composition of whole fuel consumed within a steelworks. Because the steelworks is supplied with a gap of electricity from the national grid electricity other than home power plants, we should also consider various carbon fossil fuels consumed in the external electric-power production. From this procedure, a composite fuel, which is composed of coal, heavy fuel oil and LNG, is derived as the alternative of the process gases such as BFG, COG, CFG, and LDG. In the sequential manufacturing line, IO(gas), which is the ratio of the quantity used to the quantity produced of each process gas, is increased as a functional unit proceeds to a following steel product of the next process. In the LCI system, where IO(gas) is higher than one, the IO(gas) is adjusted to nearly one. The adjustment of IO is conducted in the order of the amount of process gas used in the whole steelworks on the basis of the functional unit.

Results and Discussion. LCI analyses were carried out focusing on the alternative of the process gases for five steel products. As a functional unit goes down a lower stage, IO(gas) is increased due to the high consumption of those gases. We found a phenomenon that IO(gas) had a critical influence on the LCI results between no allocation and system expansion for the process gases through sensitivity analysis. To reduce this influence and adjust for the real situation of IO(gas), we applied an improved system expansion method to the process gases. That is, we partly substituted a process gas with LNG and rearranged the ratio between internal and external electricity (RIEE) as close as the values of IO(gas) to one.

Conclusion. As the alternative fuel for the process gases, a composite fuel was derived in the system expansion method. In addition to the composite fuel, which consisted of coal, HFO and LNG, an improved system expansion method was revised by adjusting a modified IO(gas) to nearly one, not the high value of IO(gas) for each process gas.

Recommendation and Outlook. This improved system expansion method can be applicable in the chemical industry as well as the steel industry, which have multi-function systems. Optimal LCI analysis may be achieved through the redistribution and optimization in the usage of process gases.

Keywords: Allocation; composite fuel; functional unit; life cycle inventory (LCI); process gas; steel-making process; system expansion method

1 Goal, Scope and Background

Most industrial processes yield more than one valuable product in a unit process. They occasionally have a complex system including a recycling step. The complex systems such as a multi-product system and a recycling system give rise to the allocation problems in performing a life cycle assessment (LCA). Allocation is meant to partition the input or output flows of a unit process to the product system investigated. Since the allocation problem has been one of the most important issues in the study of LCA methodology, a large number of allocation approaches for the complex system have been reported.

According to ISO 14041 and ISO/TR 14049, many methods for resolving the allocation problems are suggested. The best recommendation is to avoid or minimize the allocation, wherever possible, either by subdividing the unit process into two or more sub-processes or by expanding the boundary of systems, which have different products and are investigated for their comparison. Where the allocation cannot be avoided, the input or output flows should be partitioned according to the causal relationship between flows into and out of the system (physical relationship). The physical partitioning technique can be applied to a system to make several products of a similar function. The partitioning is based on the mass, molar content, volume and energy of each product, respectively. Where the physical partitioning cannot be used, the system inputs and outputs may be allo-

cated according to the relative economic value of the products (ISO 1998, ISO 2000). For the recycled product, no allocation is recommended in the closed loop recycling system where it is used in the same production system. While, in the open loop recycling system where the recycled product is used in another production system, the allocation is based on the physical properties, the economic value or the arbitrary number of successive uses of the recycled material (ISO 2000).

Ekvall reviewed a variety of allocation procedures mentioned in ISO (Ekvall and Finnveden 2001). A few researchers suggested various allocation methodologies on the basis of only market value or model integrated with market value (Ekvall 2000, Vogtländer et al. 2001, Tanimure et al. 2002). Other allocation studies were also reported (Kim and Overcash 2000, Weidema 2001, Frischknecht 2000). Through allocation procedures, the environmental burdens of the product system are quantitatively allocated to each product under study.

In the steel industry, the International Iron and Steel Institute (IISI) has led highly motivated LCA studies. Steel production is an energy- and resource-intensive process. A number of emissions are emitted to air, water and soil because of the great consumption of fuel and raw materials. Moreover, various types of by-products such as scrap, process gases, slag, crude light oil, tar, etc., are also produced in the steel-making process. Most of them are recycled to consume both inside and outside the steelworks. Therefore, it is important to evaluate accurately the environmental burdens or credits of the by-products. The environmental burden of scrap is quantitatively evaluated by a time decay model for input flow as well as output flow (Chung et al. 2000). Nakajima suggests a methodology for the environmental evaluation of recycled materials such as scrap, which is used in secondary metal industries by the extension of the system (Nakajima et al. 2002). The environmental burdens of other by-products are estimated by system expansion methods as mentioned in IISI reports. In particular, the IISI reports demonstrate that the process gases are replaced by coal (IISI 1998) or the national grid electricity (IISI 2002) applicable to the respective country in the system expansion method. For example, the coke plant produces coke, coke oven gas (COG, energy), which is a kind of process gas, and a few by-products (mass or energy) such as ammonium sulfate, crude light oil, tar, etc. The main product is coke, but COG is also an important co-product, which is consumed as a fuel for upstream and downstream processes. The coke plant yields some products with different functions. Physical partitioning is difficult to apply and economic partitioning is not a practical method because of both the lack of scientific basis and the practical difficulties. While, in the system expansion method, the allocation problem can be avoided by assigning all the input and output flows of the coke plant to the coke, the environmental credits for useful by-products are given to the production of both COG and other by-products. The COG and other by-products are substituted to the alternative products with a similar function in the system expansion method. So far, this method has been considered as the most compatible solution for avoiding the allocation problems, which is delineated above. However, the alternative replacement of process gases production by national grid electricity, which is suggested by IISI, is not a reasonable alternative in every country. The assumption of IISI is as follows, "Excess gas exported beyond the system boundaries is usually supplied to local power stations so as to generate electricity. Generally, the alternative fuel to these gases would be coal, fuel oil or natural gas with usually coal predominant" (IISI 2002). Nowadays, few countries produce electricity by coal as the main fuel. For example, the above assumption is wrong because electricity production by coal is below 40% and nuclear power is about 40% in Korea (KEPCO 2000).

In this study, we suggest a synthetic fuel as an alternative for each process gas in applying the system expansion method for the allocation of process gases in life cycle inventory (LCI) analysis. The composite fuel is composed of various fuels, which are consumed in the steelworks during a fixed period. This is a more reasonable substitute than either coal or national grid electricity for the subtracted operation of process gases. We also propose a modified system expansion method by resettling the amount of process gases used in the steelworks. Through this approach, LCI analyses for various steel products are conducted. We also investigate the fluctuation of air emissions such as carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x), etc. in the continuous steel products.

2 Methods

2.1 System expansion method: subtracted operation

As mentioned above, the system expansion method is one of the preferred methods to avoid the allocation problem. The target of our study is that process gases are recycled to consume within the system boundary. The process gases seem to be suitable for a closed loop recycling procedure, but they conform to an open loop recycling procedure. The open loop recycling procedure means that a product or by-product is recycled to another product system. It undergoes alterations to its inherent properties. In the case of the closed loop, the inherent properties of the recycled material are not changed (ISO 2000).

Under some assumptions of the system expansion method, the selection of a subtracted operation is very important in order to get more accurate LCI results. The subtracted operation means operation saved by the by-product. That operation has a similar function to a by-product. Process gases generated from the steel-making process are commonly used for electricity or heat production. In a system boundary, they are completely consumed within the steelworks. In some countries, they are exported to local power plants beyond the system boundaries so as to generate electricity.

A subtracted operation for the process gases consists of alternative fuel production, its transportation and combustion. In this study, the fuel corresponds to the composite fuel, which is made up of three types of fuels: coal, liquefied natural gas (LNG) and heavy fuel oil (HFO) - main fuels consumed in the steelworks investigated. Through sensitivity analysis, LCI results are compared with one another according to fuel type respectively substituted. LCI results for steel products are calculated after all the steel-making processes and background database are linked/estimated. The

system expansion method is considered at the final stage after most LCI calculations are finished. As a matter of course, it takes account of both the production and the consumption of process gases by comparing with those of each fuel. Actual estimation by the system expansion method is obtained as follows.

(Final LCI result) = (LCI result with no allocation of process gas) + (CA of process gas) – (PA of process gas) (1)

(CA of process gas) = (mining of substituted fuel + its transportation + its combustion) – (process gas combustion) (2)

(PA of process gas) = (process gas combustion) – (mining of substituted fuel + its transportation + its combustion) (3)

where CA/PA mean consumption allocation/production allocation.

2.2 In/out change of process gas with sequential functional units in LCI

In general, a steel-making process produces many kinds of steel products in sequence. From semi-finished products to finished products, the number of steel products is over 20 by their grade. More than fifty kinds of steel products are categorized by the names of goods. Moreover, hundreds of products are classified by their thickness or uses. All of these steel products can be the functional units in LCI analysis. Some functional units may be intermediate input materials in the other functional units. In this way, the sequential functional units in the steel industry have a kind of hierarchical structure. And as a functional unit goes down a lower stage, a peculiar phenomenon sometimes occurs. The peculiar phenomenon is that the total amount of process gas consumed in other processes is more than that of the process gas generated from a steel-making process on the basis of the functional unit. It is a theoretically logical result, but it seems unnatural. We will introduce a few cases in the next section for this situation. Here, we will describe some equations to estimate the amount of both consumption and production of process gases in performing an LCI.

In the steel-making process, we set the amount of product (P) in the i_{th} process stage to P_i. The P_i is transported to $(i+1)_{th}$ process stage. M_{i+1} means the amount of P_i used in the $(i+1)_{th}$ process stage. P_i', which is the relative amount of P_i on the basis of a functional unit, is defined as Eq. (4). Here, i should be over one (i ≥ 1).

$$P_i' = \frac{M_{i+1}}{P_{i+1}'} \tag{4}$$

The amount of a process gas consumed in the i_{th} process stage is defined as $I_{gas,i}$. BFG, COG, CFG, and LDG correspond to the gas. The description of those gases is explained in detail in Section 3.1. $I_{gas,i}'$, which is the relative amount of $I_{gas,i}$ on the basis of a functional unit, is defined as Eq. (5) and (6) according to i.

$$i \le n-1, \quad I_{gas,i}' = \frac{I_{gas,i}}{P_i'} \tag{5}$$

$$i = n, \; I_{gas,i}' = \frac{I_{gas,i}}{P_i} \tag{6}$$

O_{gas} indicates the amount of each process gas generated from a steel-making process. It is equal to the sum of gas usage consumed in all processes. If we add up $I_{gas,i}'$ on the basis of a functional unit, however, O_{gas}' is not necessarily equal to the sum of $I_{gas,i}'$ as seen in Eq. (9).

$$I_{gas}' = \sum_{i=1}^{n} I_{gas,i}' \tag{7}$$

$$\sum_{i=1}^{n} O_{gas,i} = \sum_{i=1}^{n} I_{gas,i} \tag{8}$$

$$\sum_{i=1}^{n} O_{gas,i}' \ne \sum_{i=1}^{n} I_{gas,i}' \tag{9}$$

We define the ratio between the input and output of each process gas with sequential functional unit in LCI as IO(gas), like Eq. (10) and (11). Detailed explanation with examples will be shown in Section 3.2.

$$\sum_{i=1}^{n} I_{gas,i}' > \sum_{i=1}^{n} O_{gas,i}' \rightarrow \frac{\sum_{i=1}^{n} I_{gas,i}'}{\sum_{i=1}^{n} O_{gas,i}'} = IO(gas) > 1 \text{ (for high i)} \tag{10}$$

$$\sum_{i=1}^{n} I_{gas,i}' < \sum_{i=1}^{n} O_{gas,i}' \rightarrow \frac{\sum_{i=1}^{n} I_{gas,i}'}{\sum_{i=1}^{n} O_{gas,i}'} = IO(gas) < 1 \text{ (for high i)} \tag{11}$$

3 Case study for Steel-making Process

3.1 Description of steel-making process and various s teel products

As mentioned above, tens of steel products are produced from a steel-making process with many by-products such as scrap, slag, process gases, etc. Among many steel products, we select five typical steel products as functional units of life cycle inventory analysis. The system boundary of the steel products covers an area ranging from the resources extraction, their transportation to the works utilities production, such as electricity, steam and hydrogen, etc., to manufacturing processes of the steel products. **Fig. 1** shows a series of processes such as iron-making, steel-making, continuous casting, and rolling. Iron-making is a process which isolates and extracts iron from iron ores by burning cokes. Lime calcining, sinter, coke, and blast furnace (BF)/ COREX processes are included in the iron-making process. Coke is produced by heating coking coal without oxygen at high temperatures between 1000°C and 1300°C. When cok-

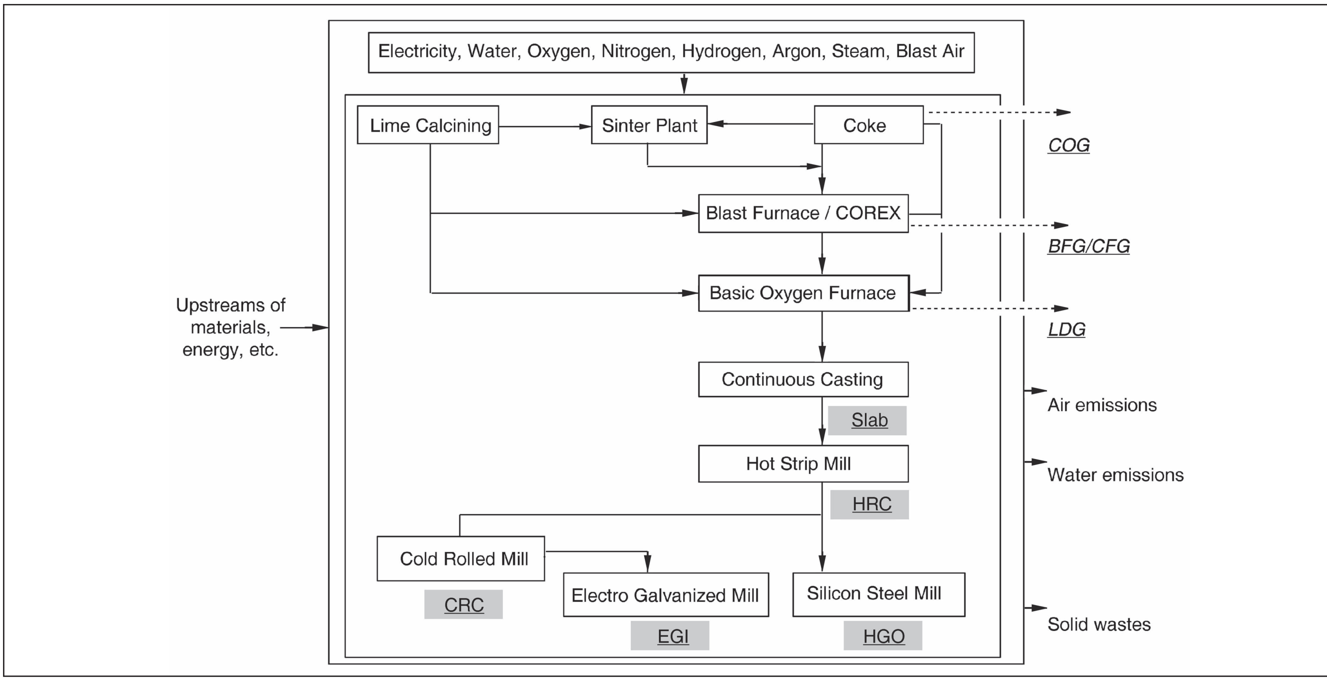

Fig. 1: A simplified schematic steel-making process tree and system boundary for LCI of various steel products (Slab, HRC, CRC, EGI, HGO)

ing coal is burned in the coke plant, coke oven gas (COG) is also generated as a by-product gas. COG is used as a fuel in most steel-making processes as well as utility plants such as power plants, oxygen and hydrogen plants, etc. The coke is transported to the blast furnace with graded sinter, where it is melted. From the blast furnace, hot metal is produced with blast furnace gas (BFG). BFG is also consumed as a fuel like a by-product gas in most plants. COREX is a new factory substituting a BF process(IPPC 1998). Hot metal and COREX furnace gas (CFG) are also produced together. CFG is consumed as a fuel in COREX, coke, and power plants. In the steel-making process, the hot metal is poured together with steel scraps and additional metals into a basic oxygen furnace (BOF). A high-pressure stream of pure oxygen is injected into the hot metal, transforming the impurities into gases and slag. Linze donawitz gas (LDG) generated from BOF is consumed as a fuel in some processes within the works. The crude steel is poured into a continuous caster, which produces semi-finished products such as slab and bloom. The semi-finished slab is reheated and fed through a hot strip mill to make hot rolled coil (HRC). And the HRC is carried to a cold rolled mill to make cold rolled coil (CRC) and electrolytic galvanized steel sheet (EGI). CRC and EGI have the same processes ranging from pickling line, tandem cold mill, continuous annealing line, to skin pass mill within the cold rolled mill. While CRC is lastly produced through just a simple shearing line, a little complex electrolytic galvanized line (EGL) is added for the production of EGI. Now the works produce top grade EGI with state-of-the-art technology. The last steel product in our functional units is the electrical steel manufactured from a silicon steel mill (SSM). From the SSM, two kinds of electrical steel, non-oriented electrical steel (NO) and grain-oriented electrical steel (GO), are produced. The object of the investigation is high functional, grain-oriented electrical steel (HGO) among various GO. The directional property of HGO is more reinforced in the rolling direction than common GO and therefore features low core loss and high induction. It is used for iron cores of power transformers (POSCO 2001).

4 Results and Discussion

It is very important what kind of method an LCA practitioner chooses in performing an LCA among various allocation methodologies, because the results of LCI and LCA are influenced by the allocation method. After applying an allocation methodology to a multi-output process, we generally perform sensitivity analysis for the verification of results. As described above, the environmental impacts of process gases generated from the steel-making processes are substituted with similar functional operations of the system expansion method. In this study, we show the environmental impacts with the selected allocation method through LCI case studies for steel products. And we are going to suggest more improved LCI results for each steel product using a modified allocation rule.

All data for LCI are obtained from several sources as we mentioned in our last works (Moon et al. 2003). Data are generally divided into two parts - background data and foreground data. The background data are based on DEAM and domestic LCI database. The DEAM database corresponds to a single database set of TEAM software (Ecobilan 1998). It was made after mid 1990 and has been updated until now. The domestic LCI database was accomplished recently. The foreground data deals with the data for all the steel-making processes and utility plants within the steelworks collected in 2000. As an analytical tool for LCI, we used the LCA software named POEM2, which was developed by our team a few years ago (Moon et al. 2003).

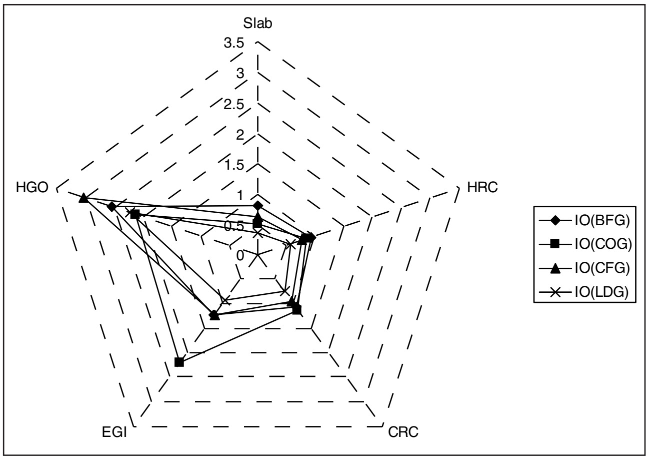

Fig. 2: Comparison of IO(gas) for each functional unit in LCI

As shown in Fig. 1, we selected five steel products; Slab, HRC, CRC, EGI, HGO, for the functional units of LCI case studies. **Fig. 2** shows the IO(gas) for each functional unit. In our system boundary, four types of process gases are produced from the steel-making processes. To Slab and HRC levels, the amount of generated process gases is less than that of used gases. But from the CRC, the situation reverses itself in the case of BFG and COG. Furthermore, in the production of HGO, which is a high energy intensive steel product, all the process gases are consumed more than two times compared with the amount of process gases produced from the specific processes. This is due to a sequential production of the steel products. As a steel product goes down the downstream stage, the amount of production for the steel product decreases. The final amount of HGO to be sold is no more than 0.1% of total amounts of steel products. Therefore, by analyzing the LCI result of the steel product through additional processes for high performance, we found the above phenomena that IO(gas) was over one. This is the reason a high-grade steel product consumes more energy than a low-grade one. Considering the whole steelworks, the net energy balance of the process gases is zero, as expressed by Eq. (8). But, when we investigate LCI according to the product level, its net energy balance is not zero as in Eq. (9).

Fig. 3 shows the difference of carbon dioxide (CO_2) between the system expansion method and no allocation for process gases according to various steel products in LCI. In the system expansion method, five alternative fuels such as coal, HFO, LNG, electricity and composite fuel are chosen for sensitivity analysis. The composition of composite fuel is indicated in **Table 1**. We use Composition B not Composition A. The Composition A is just the ratio of each fuel used in the steelworks in a year while Composition B means the ratio considering the fuels consumed for the production of external electricity as well as the total fuels consumed in the steelworks. It is considered that the latter is more reasonable than the former in terms of total energy usage. In 2000, the external electricity in the steelworks occupies about 30% of the total electricity usage. 70% of the electricity used in the steelworks is produced in its power plants. In 2002, about 80% of electricity is produced in the independent power plants in the works. Anyway, the portion of coal in composite fuel is decreased to 94.5%. It is increased to use HFO and LNG. When the IO(gas) of a steel product is around one, the standard deviation (SD) of CO_2 value in LCI of the product is small. For example, in case of CRC, the SD of CO_2 is below 15 kg/ton of CRC while, in cases of HGO having high IO(gas), the SD of CO_2 is no less than 932 kg/ton of HGO. That is to say, according to IO(gas) of each product, the fluctuation of CO_2 is severe. Those same phenomena occurred in other emissions such as SO_x and NO_x, as seen in **Fig. 4** and **Fig. 5**. Judging from the shape of the graph in Fig. 3 to Fig. 5, as it is close to a regular hexagon, the SD is nearly zero.

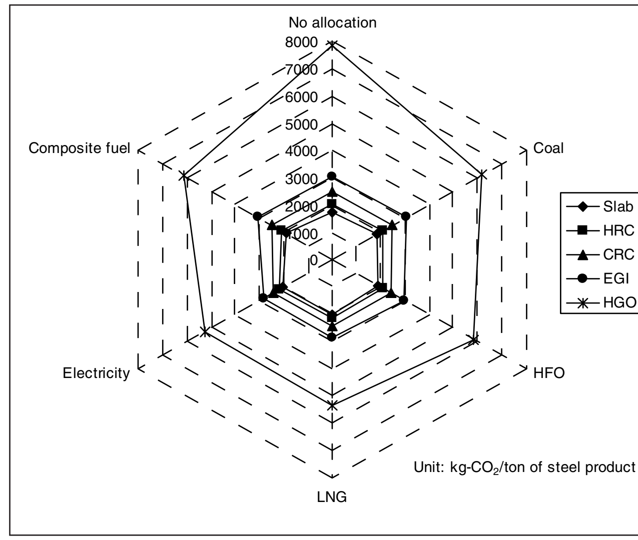

Fig. 3: Difference of carbon dioxide (CO_2) between no allocation and system expansion method for process gases according to five steel products in LCI

Table 1: Composition of energy containing carbon consumed in the steel works during 1 year

Fuel	Composition A [a]	Composition B [b]
Coal	97.9%	94.5%
HFO	0.9%	3.2%
LNG	1.2%	2.3%
Total	100%	100%

[a] This composition is based on the total fuel consumed in the steel works with the exception of external electricity.
[b] Contrary to composition A, composition B includes external electricity received from KEPCO, as well as the total fuel consumed in the steel works. External electricity is comprised of grid electricity such as nuclear, thermoelectric, hydroelectric powers, etc. Among them, only thermoelectric power is included to composition B considering CO_2 emission source.

In case that IO(gas) is over one, the status is different from a real situation, because the amount of process gases generated from the steelworks are not less than those used. Besides, if a semi-finished steel product is sold to other silicon steel mills and LCI of the HGO is performed, the result is

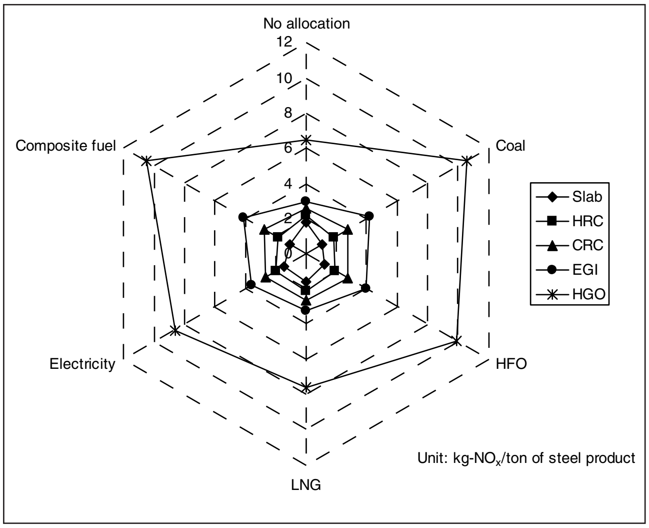

Fig. 4: Difference of nitrogen oxides (NOx) between no allocation and system expansion method for process gases according to five steel products in LCI

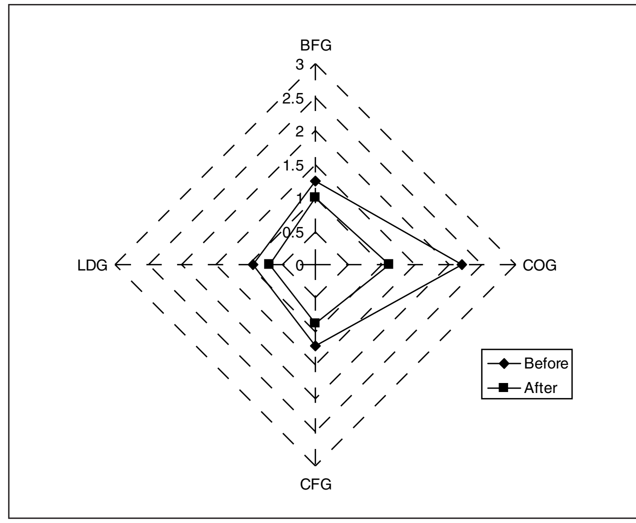

Fig. 6: Comparison of IO(gas) for EGI before and after adjusting the value of IO(gas) to nearly one

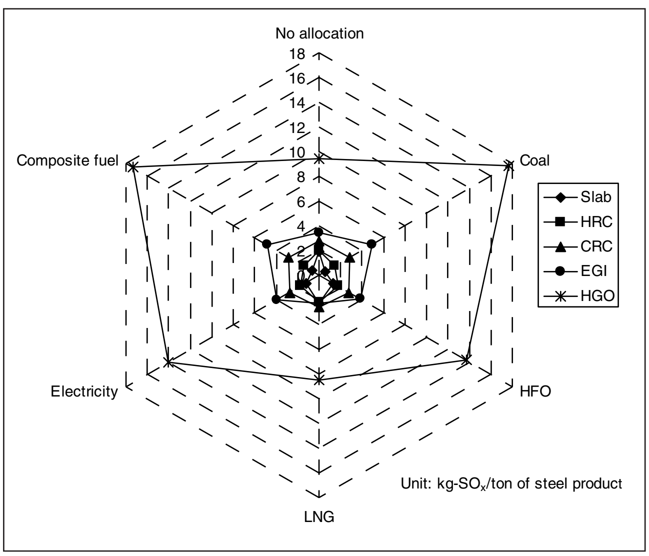

Fig. 5: Difference of sulfur oxides (SOx) between no allocation and system expansion method for process gases according to five steel products in LCI

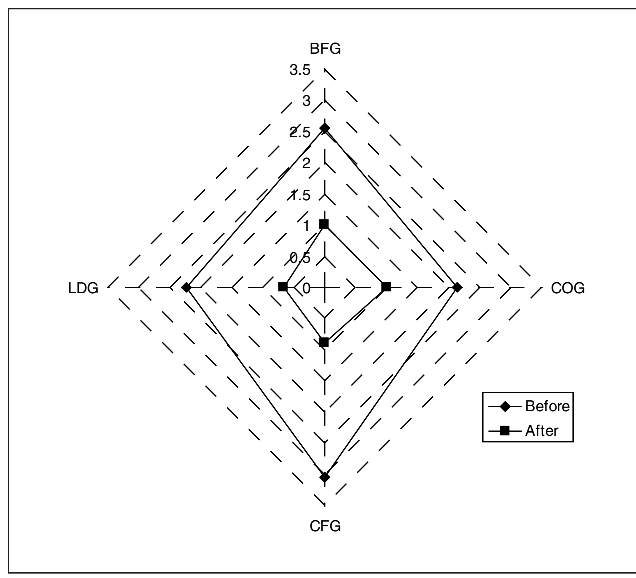

Fig. 7: Comparison of IO(gas) for HGO before and after adjusting the value of IO(gas) to nearly one

inconsistent to the above case. We suggest an improved system expansion method for the process gases. That is, IO(gas) is set to nearly one within the limits of the possibility. As shown in **Fig. 6** and **Fig. 7**, IO(gas) for EGI and HGO is set to one in the order of BFG, COG, CFG and LDG. The order is based on the total amount of process gas used in the steelworks by functional units. The tetragons are shrunk to a smaller shape of quadrangles. The shrinking procedure for IO(gas) is as follows. When IO(gas) is over one, the largest portion of process gases is consumed in the independent power plants within the steelworks. COG is widely used as a fuel in overall steel-making processes. Therefore, above all, we substituted COG for LNG consumed in the last downstream process. And then we rearranged the ratio between internal and external electricity (RIEE) consumed in the steelworks. That is to say, the RIEE of HGO is changed from 0.699:0.301 to 0.168:0.832. This is based on the fact that most other steelworks use the external electricity received from Korea Electric Power Corporation (KEPCO). In case of EGI, the RIEE is changed to 0.469:0.531. Additionally, owing to the shrinking, the emissions in LCI are adjusted to the new values as indicated in **Table 2**. Those improved emission values in LCI are considered to be more general and acceptable results. From the LCI results of EGI and HGO, the amount of CO_2 is decreased by 7% and 16%, respectively. In the end, the system expansion method modified by using the composite fuel ratio provides better LCI results for the steel products.

Table 2: Selected LCI results for EGI and HGO before and after adjusting the value of IO(gas) to nearly one

	EGI (kg/ton of EGI)		HGO (kg/ton of HGO)	
Air Emissions	**Before**	**After**	**Before**	**After**
CO_2	3062.53	2845.57	6164.55	5174.06
NOx	4.85	3.24	17.39	14.09
SOx	4.09	4.05	10.48	8.23

5 Conclusion

Instead of the existing coal or electricity as the alternative fuel for the replacement of the process gases, a composite fuel comprised of coal, HFO and LNG was applied. True improvement of this study was that we suggested a correct solution for the allocation problem of process gases generated from integrated steelworks. The portion of coal in the composite fuel is reduced to 94.5%. From the LCI case studies of various steel products, we found that because the shape of the graph for LCI results is close to a regular polygon according to the allocation methods, the SD of those values is nearly zero. The LCI results are influenced by IO(gas). By adjusting the value of IO(gas) to nearly one in the case of EGI and HGO, its CO_2 value is reduced to 2845.57 kg/ton of EGI and 5174.06 kg/ton of HGO, respectively. Through this improved system expansion method, we performed LCI of each steel product repeatedly, and could obtain more general and accurate LCI results.

6 Recommendation and Outlook

The suggested system expansion method can be applied to a chemical industry with a complex process system, because many by-products generated from the process are recycled within the system boundary. When nationwide LCI databases are constructed through the method, more reliable and accurate results can be obtained because of a small fluctuation of average values in each functional unit. If redistribution or optimization for the usage of process gases is attained in the future, their complete handling will be achieved.

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